TITLE: Resonant Waveguiding and Lasing in Structures with InAs Submonolayers in an AlGaAs Matrix

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Resonant waveguiding and lasing in structures with InAs submonolayers in an AlGaAs matrix

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Recently significant interest arose in semiconductor heterostructures with submonolayer (SMs) insertions of narrow gap material. Spontaneous formation of arrays of uniform two-dimensional islands has been demonstrated for II–VI and III–V materials systems [1, 2]. These structures, which can be considered as arrays of quantum dots (QDs) in view of the lateral sizes involved (about 4–5 nm) exhibit unique optical properties: increase in the exciton binding energy due to lateral confinement, high photoluminescence (PL) efficiency and large oscillator strength [3] even for ultrathin coverages. Besides, it was shown that for stacked CdSe SMLs in an ZnMgSSe matrix lasing can occur without external waveguiding as a result of the modulation of the refractive index near the exciton resonance energy [4–6].

In this work we study optical properties III–V structures with SML InAs insertions in an AlGaAs matrix. Lasing under photoexcitation is demonstarted for the structure without external optical confinement. Lasing occurs on a low energy side of the exciton resonance at low excitation densities pointing to the importance of this structures for improved optical confinement in AlGaAs injection laser operating in the visiblel range, excitonic waveguides and self-adjusted microcavities.

Investigated structures were grown by molecular-beam epitaxy on GaAs(100) substrate. First a 0.3 μm-thick GaAs buffer has been grown followed by a 0.7 μm-thick $Al_{0.32}Ga_{0.68}As$ layer. The active region comprised of 20 GaAs quantum wells of 1 nm width separated by 5 nm $Al_{0.32}Ga_{0.68}As$ spacer layers. The average Al composition of the active layer was only by 5 % lower than in surrounding matrix resulting in a strong penetration of the lightwave in the GaAs matrix if no resonant enhancement of the refractive index in the active layer is provided. InAs insertions having an average 0.5 ML thickness were inserted in the centre of these GaAs quantum wells. From both side active region was confined by thin 10 nm $Al_{0.4}Ga_{0.6}As$ layers to prevent transport of carriers towards the surface and the semiinsulating substrate. A 100 nm-thick $Al_{0.32}Ga_{0.68}As$ layer followed by a 10 nm GaAs cap layer were grown on top. Growth temperature for buffer and cladding layers was 600 °C. Active region was grown at 485 °C to prevent reevaporation and surface segragation of In.

Fig. 1 shows PL, PL excitation (PLE) and optical reflection (OR) spectra of the investigation structures. PLE and OR spectra have features at energies of 1.761 eV and 1.801 eV denoted as QD1 and QW, respectively. As revealed in resonant PL and excitation density studies, the PL peak is composed of two lines.

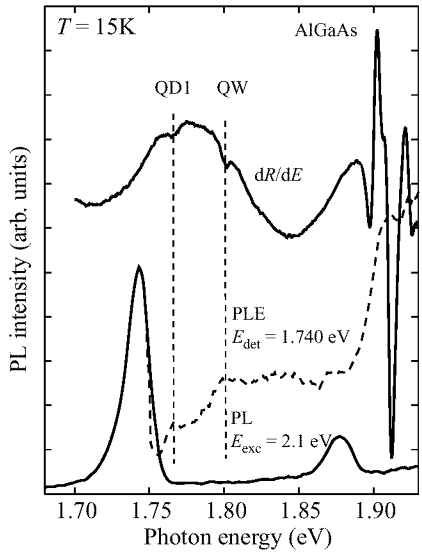

Fig. 1. PL, PLE and OR spectra of the investigated structure.

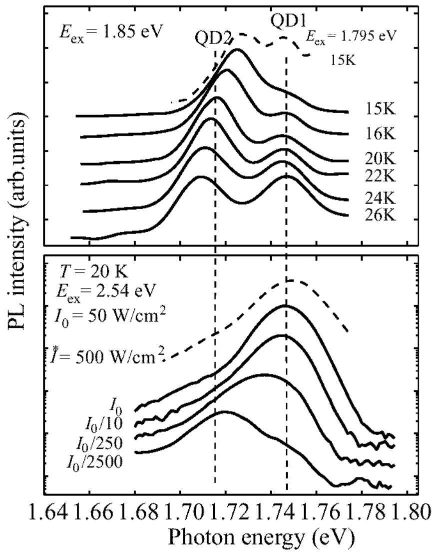

Fig. 2. PL spectra at different temperatures and excitation by light with photon energy 1.85 eV (a) and different excitation densities (b).

Temperature dependence of the PL spectra for exciting photon energy of 1.85 eV (a) and the excitation density dependence (b) of the PL spectra are shown in Fig. 2. Temperature variation in a range of 15–25 K results in significant changes in the PL spectrum. QD2 line intensity decreases with respect to the QD1 line and it shifts significantly toward smaller photon energies. The spectral position of the QD1 line is not changed. At low temperatures and low excitation densities QD2 line dominates in the PL spectrum (Fig. 2b). Increase in excitation density results in rapid saturation of the intensity of QD2 line and QD1 line starts to dominate.

Investigated structure represents a stack of narrow GaAs quantum wells (QWs) with microscopic localization areas induced by InAs QDs. Existence of two peaks (QD1 and QD2) in the PL spectrum at low excitation density indicates formation of two types of QDs. Relative increase in the QD1 line intensity with respect to the QD2 line one points to low density of QDs responsible for QD2 line. Significant long wavelength shift of the PL maximum with temperature increase is typical for recombination via QDs states [7]. Increase in temperature leads to evaporation of carriers from small QDs which determine the short wavelength side of the PL spectrum. This results in significant (as compared to the temperature dependence of the band gap) shift of the PL maximum toward low photon energies. Narrow temperature range in which the QD2 PL spectrum changes points to low density of such QDs. On the other hand, the temperature shift of the QD1 line is close to the temperature dependence of the AlGaAs band gap pointing to high density of related states. QD2 states can be related to islands having two-monolayer height or to vertically-coupled islands.

PL spectra are changed remarkably for excitation energy below and above 1.8 eV (Fig. 2a). Calculations of the heavy-hole exciton energy level in narrow GaAs QW and

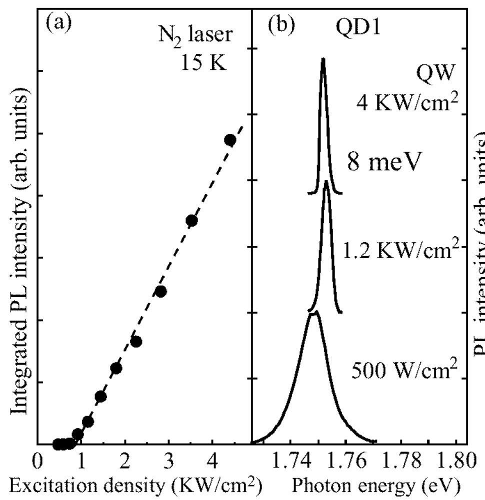

Fig. 3. Dependence of the integral PL intensity on pumping level (a) and PL spectra at different pumping (b).

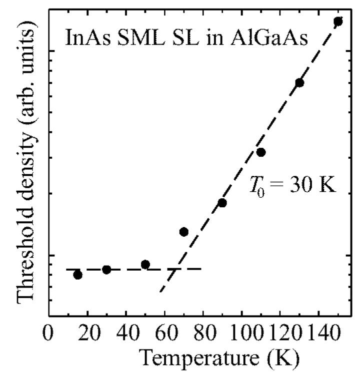

Fig. 4. Temperature dependence of the threshold excitation density.

the comparison of PL, PLE (e.g. step-like PLE behaviour at 1.8 eV) and OR spectra (sharp oscillation occurs at 1.8 eV) points that the states at this energy are related to the onset of the QW states.

To study lasing the 1 mm-long Fabri–Perot cavity was cleaved. The luminescence was excited from the surface using a pulsed N_2 laser beam focused in a stripe. Fig. 3a shows dependence of the integral PL intensity detected from the edge of the structure versus excitation density. A strong enhancement of the slope efficiency occurs at 800 W/cm^2 (see Fig. 3a). We attribute this behavior to lasing, which is further confirmed by the narrowing of the emission line (Fig. 3b). The lasing occurs at 1.750 eV, which is in the very vicinity of the exciton feature QD1 in the OR spectrum (1.761 eV). Thus, lasing occurs via the exciton ground state in InAs SML QDs. The threshold excitation density at 15 K is 800 W/cm^2. The calculated corresponding injection current density value is only about 200 A/cm^2. This value of threshold current is an upper estimation due to unknown surface leakage of nonequilibrium carriers for their near surface excitation using ultraviolet laser.

In Fig. 4 the temperature dependence of threshold excitation density is shown. At temperatures below 50 K the threshold excitation density is almost temperature-insensitive. This behaviour agrees with the QD nature of excitons trapped at InAs islands. Qualitatively similar dependence is observed for injection lasers with three-dimensional In(Ga)As/(Al)GaAs QDs [8]. At higher temperatures the threshold density increases exponentially with characteristic temperature of $T_0 = 30$ K. Such an increase of the threshold intensity results from thermal evaporation of carriers from InAs SML islands to the QW continuum. The maximum temperature for lasing for maximum excitation density used in our experiment was 170 K. We note that the temperature stability of the threshold density can be significantly improved by using wider gap cladding layers, narrower GaAs quantum wells, or by using a concept of vertically-coupled QDs.

To conclude, lasing without external optical confinement is demonstrated in III–V structures structures with InAs submonolayers in an AlGaAs matrix. We expect that these structures are very attractive for improvement of optical confinement in AlGaAs and InGaAsP lasers operating in visible spectral range, for creation of excitonic waveguides and vertical cavity lasers with self-adjusted cavity mode.

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